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THE EFFECTS OF CHARACTER STROKE WIDTH ON THE VISIBILITY OF A HEAD-COUPLED DISPLAY

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SUMMARY PAGE

THE PROBLEM

Experiments on visual-vestibular interaction with head-fixed displays have involved many different display types. This experiment is one of a series directed toward obtaining systematic information of effects of display characteristics on visual performance when man is in motion.

FINDINGS

When man is required to view a head-fixed display during body movement, his reading performance is degraded because of inadequate suppression of the vestibulo-ocular reflex. An experiment has been conducted to ascertain whether visual performance can be enhanced if the characteristics of a visual display are modified. Subjects were exposed to a 0.025 Hz angular oscillation about the yaw axis with a peak velocity of $\pm$ 120°/s. During both the high and low velocity phases of the waveform there was a significant improvement in reading rate when either the stroke-width of the character was decreased or the inter-character spacing was increased. The results indicate that displays consisting of well-spaced characters composed of bright thin lines are the most suitable for use in vibration conditions.

INTRODUCTION

There have been a considerable number of experiments in recent years in which the ability of human subjects to suppress inappropriate eye movements of vestibular origin has been assessed (3,7,9,10,16). In all these experiments, in which the subject viewed a display coupled to the head, many different types of display were used, varying in character form, luminance and contrast. All of the experiments have indicated a marked decrement in visual performance at velocities and frequencies of head movement at which the subject was unable to completely suppress the vestibulo-ocular reflex. In such conditions the decrement in visual performance arose because the relative movement of the eye with respect to the display caused smearing of the image on the retina and consequent blurring of the characters of the display.

In recent experiments, Barnes and Smith (4) have investigated the effects of relative velocity of the image across the retina on the ability of the human subject to correctly interpret a simple numerical display. The result of this experiment indicated that factors such as the luminance, contrast and size of the display had a most marked effect upon the velocity level at which the moving display could be correctly interpreted with equal probability. It became apparent from consideration of the probable mechanisms involved in the processing of such moving images by the visual system, that the different effects could be explained in terms of the degree and extent of the blurred trail left by the passing images on the retina. As a consequence it was hypothesised that the ratio of stroke-width to breadth of the characters in the display might also affect the subject's ability to read the display. In order to test this assumption an experiment was devised in which the stroke-width and character spacing of the display were varied in experimental conditions involving suppression of the vestibulo-ocular reflex.

PROCEDURE

The subject was seated within a large rotating cabin (NAMRL Human Disorientation Device (HDD)) with the head at the center of rotation. A visual display was fixed to the body of the cabin directly in the line of sight of the subject (Fig. 1). The display consisted of a series of randomly sorted digits (excluding 1's and 7's) in a 5 x 8 format as shown in Fig. 2. The display was formed by projecting transparencies of the digit matrix on to a small back-projection screen made of Plexiglass which was placed at right angles to the subjects line of sight. The display was viewed binocularly by the subject through a mirror placed at 45° to the line of sight. A total of 60 different digit matrices were displayed to the subject in a randomised and balanced sequence.

There were five different character stroke widths for the digits within each matrix. The largest was such that the stroke width was equal to one third of the character width (i.e., similar proportions to a Snellen character). The smallest had a stroke-width equal to one ninth of the character width, the remainder being graded proportionately between these two extremes. The digits within the matrix were spaced in three different ways as follows:

In type A display format the digits were spaced in such a way that the distance within the two vertical limbs of each character was equal to the space between the right and left hand vertical limbs of adjacent characters.

The vertical limbs thus appeared in equal mark-space ratio with the background spaces. This can be expressed mathematically by the relationship:

$$Csp = Cw - 2.0\ Csw,$$

where Csp = inter-character spacing; Cw = character width; Csw = character stroke width.

Three examples of the type A format are shown in Fig. 2A.

In type B display format the digits were spaced so that the between character spacing was the same regardless of stroke width and was equal to the smallest inter-character spacing for the type A format. That is:

$$Csp = Cw/3$$

Thus type B and type A digit matrices with the largest stroke width had an identical format (Fig. 2B).

Type C digit format was similar to type B but had an inter-character spacing equal to the largest intra-digit spacing for type A matrices. That is:

$$Csp = Cw7/9$$

Type C and type A digit matrices with the smallest stroke width were nearly identical in format (Fig. 2C). An error in the production process yielded an intercharacter spacing in Type C format 7.0 percent greater than planned.

The digits appeared white against a black background. There was no additional light source within the cabin and the subject was only able to see the digit matrix and its immediate surround. In an attempt to keep the overall luminous flux constant and thus maintain the same level of visual adaptation, the luminance of the character strokes was designed to be inversely proportional to the stroke-width, by incorporating appropriate neutral density filters into the transparencies. However, measurement of the luminance for each stroke-width revealed that this relationship had not been achieved, the average values for the luminance of the digit and the background being as follows:

Csw/Cw	2/18	3/18	4/18	5/18	6/18
Digit Luminance (cd/m^2)	87.4	85.6	64.4	56.1	47.3
Background Luminance (cd/m^2)	0.5	0.8	0.8	0.9	1.3

The major discrepancy was in the low luminance level for the smallest stroke-width character format. The significance of this is assessed later in the discussion.

The height of each digit and the spacing between rows of digits was maintained constant through the whole range of character formats. The height of each digit subtended 10 min arc at the eye, the width of each digit, 6 min arc. The overall height of each matrix subtended 1.28°, the overall width varied between 0.97° and 1.40°, depending on the inter-character spacing.

The subject was exposed to a sinusoidal oscillation about the vertical axis of the head, thus stimulating the horizontal semicircular canals to produce a vestibular nystagmus in the horizontal plane. The frequency was maintained at 0.025 Hz and the peak velocity was $120^{o}/s$. The task for the subject was to read as many digits as possible from the matrix of digits presented on the visual display system. Each matrix was displayed for a period of 10s, there being four presentations during each 40s period of a single stimulus cycle. The presentations were arranged to coincide with the two periods of maximum and minimum eye velocity during each cycle, as illustrated in Fig. 3. A simple logic circuit detected zero-velocity crossover points of the stimulus waveform and arranged for the digit matrix to be changed at four equal intervals (10s) in synchrony with the start of each cycle. Since the aim was to present the matrices during the periods of maximum and minimum eye velocity and it is known that at 0.025 Hz there is a phase lead of approximately 25^{o} (5,13) an appropriate shift of presentation times with respect to head velocity was incorporated into the logic circuit as indicated in Fig. 3. The experiment was carried out on 12 subjects, all of whom had normal 20/20 or better static visual acuity in each eye and no known disorder of the vestibular apparatus.

RESULTS

Type A character format.

The digit matrices with the smaller stroke-widths were easier to see during both the high and low velocity phases of the stimulus because there appeared to be less overall blurring of the individual characters. The subjective impression was supported by the reading performance measured in terms of the number of digits read correctly during the 10s presentation period, (Fig. 4A). Analysis of variance[1] revealed a highly significant ($P < 0.001$) increase in the number of digits rea as the stroke-width was decreased. The mean levels indicated that during the high velocity phase, approximately twice as many of the smallest stroke-width digits could be read as those with the largest stroke-width corresponding to the conventional Snellen characters. A smaller (33%) increase in performance was also observed during the low velocity phase of the waveform.

As expected, there was also a highly significant ($P < 0.001$) difference in performance between the high and low velocity phases of the waveform. There was no significant difference between responses to left- or right-going movement.

Type B character format.

In contrast to the performance with the type A characters there was no significant effect of stroke-width on reading performance when viewing the type B characters, for either the high or low velocity phases of the waveform. There was a highly significant ($P < 0.001$) difference in performance for the two velocity levels, as would be expected. Subjectively, this was borne out by the impression that the closer spacing between the digits of the matrix made them more difficult to distinguish regardless of the actual stroke-width. The overall performance was depressed throughout the range of stroke-widths to mean levels which were close to the mean performance when viewing the type A character with the largest stroke-width.

Type C character format.

The performance when viewing the type C character format, in which there was the widest spacing between digits, was similar to the performance with the type A format. There was a highly significant ($P < 0.001$) increase in reading rate as the stroke-width was decreased, the mean levels exhibiting an 82% change for the high velocity phase and a 20% change for the low velocity phase. Again, there was a highly significant ($P < 0.001$) increase in performance from the high to the low velocity phase of the motion stimulus, but no significant effect of the direction of movement. Subjectively, the wider spacing between characters facilitated the task of distinguishing adjacent digits within the matrix.

A comparison of type A and type C formats revealed no significant difference in reading performance for any of the stroke-widths, for either the high or low velocity phases of the stimulus waveform.

Eye movements.

Although eye movements were recorded throughout the experiment, the electronystagmographic method did not allow the small eye movements to be measured with sufficient accuracy in order to compare responses in the different experimental conditions. The recordings did reveal, however, that all subjects had a potent vestibulo-ocular response when recorded in darkness and were able to suppress this reflex response during presentation of the visual display to such a degree that in the majority of subjects eye movements were reduced in amplitude to less than $\pm 1^{\circ}$.

DISCUSSION

The results of this experiment support the hypothesis, discussed in the introduction, that increasing the spacing between and within the characters of the visual display enables reading performance to be enhanced because of the reduction in blurred image overlay from one character to another. The performance for the type A character format, in which the between- and within-character spacing was identical throughout the range of stroke-widths, exhibited a straight-forward increase as the stroke-width was decreased. However, the results from the type B and C character formats indicated that a decrease in either the between-character spacing or within-character spacing was sufficient to cause performance to fall to levels comparable with those for the thickest stroke-width in the type A character format. Thus, the performance for the type B format in which the spacing between characters was constant and equal to one third of the character width, was not improved as stroke-width was decreased. This presumably arose because the narrow gap between characters caused overlap of their blurred images as they became smeared across the retina of the moving eye. However, in the type C format, the gap between characters was much wider (equal to 7/9 of character width) and thus overlap of adjacent characters was less likely. Nevertheless, performance was still low if the stroke width was high, presumably because the consequent reduction in the space within the characters caused overlapping of the blurred images of the vertical character strokes, leading to problems of character recognition.

Previous experiments (4) have shown that the luminance of the display can have a marked effect upon the visual performance when there is relative movement between the eye and the viewed display. When the eye is adapted to high luminance levels transient images formed on the retina decay more rapidly than under low luminance conditions (15). Movement of the eye with respect to a display produces a blurred image trail and the extent of this blurring is less if the visual response decays more rapidly. Thus, under high luminance conditions, the extent of the blurred trail is reduced and character discrimination is improved because there is less overlapping and in-filling between characters. The luminance levels used in the experiment described here were well within the photopic range where decay rates are highest. There would probably be an even greater effect of character stroke-width if the luminance levels were reduced to the scotopic or mesopic range because of the resultant increase in the breadth of the blurred image trails left by the vertical strokes of the characters as they move across the retina.

An attempt was made in this experiment to keep adaptation levels constant between presentations by increasing the luminance level of the smaller stroke-width characters. As noted in the Methods section this was not completely successful but it is unlikely that this factor would heavily influence the results. The luminance levels used were well within the photopic range in which decay rates of the visual image are relatively constant and at the highest level (15). In keeping overall luminance level approximately constant there was a large change in contrast with the background which ranged from 175 for the smallest stroke-width to 40 for the largest stroke-width. However, experiments in which the static reading performance of different character formats has been assessed (14) indicate that for the high contrast levels used in this experiment there is unlikely to be an effect of contrast on reading rate. This is partially supported by the reading performance associated with character format B (Fig. 4B) for which there was no significant change despite the wide range of contrast conditions because the digits were too closely spaced within the matrix.

The difference in reading performance between the high and low velocity phases of the stimulus waveform is in accord with the results of several previous experiments (1,3,6,10,11,12). The suppression of the vestibulo-ocular response through visual fixation can be accomplished much more easily when the stimulus is of low velocity and consequently there is less blurring of the visual world (4). It is a little surprising that there was a significant increase in performance with decrease of stroke-width during the low velocity phase, since experiments by Gilson et al (9) indicated negligible eye movement during such periods. However, more recent experiments (2) have shown that even during this phase there is still likely to be some relative eye movement with respect to the display which is clearly sufficient to cause a performance decrement as demonstrated by Benson & Cline (6).

The effect on reading performance of the ratio of stroke-width to height for letter characters was investigated for static conditions by Crook et al. (8). An optimum reading rate of 2.3 characters/s was obtained for a ratio of 20%, corresponding to the largest stroke-width character in the present experiment. Performance decreased slightly for ratios of 9.8% and 30%. This is in contrast to the performance changes shown in Fig. 4 A & C for which a decrease in the ratio of stroke-width to height from 20% to 6.7% led to an increase in reading rate from 1.8 to 2.6 characters/s during the low velocity phase of the waveform. Thus, it would appear that the display characteristics most suitable for optimum static performance are not necessarily the most suitable for vibration conditions.

The results of this experiment are of practical importance to the designers of helmet-mounted display systems. Such systems are susceptible to degradation of the visual display if there is movement of the head induced by aircraft vibration. This arises as a result of the inability of the human subject to adequately suppress eye movements of vestibular origin at the higher frequencies (principally 1-10 Hz) encountered in aircraft flight, (1,3). These experiments indicate that the problems of image smear caused by the unsuppressed eye movement may be minimized if the characters of the display are composed of thin bright lines and if there is adequate spacing between characters.

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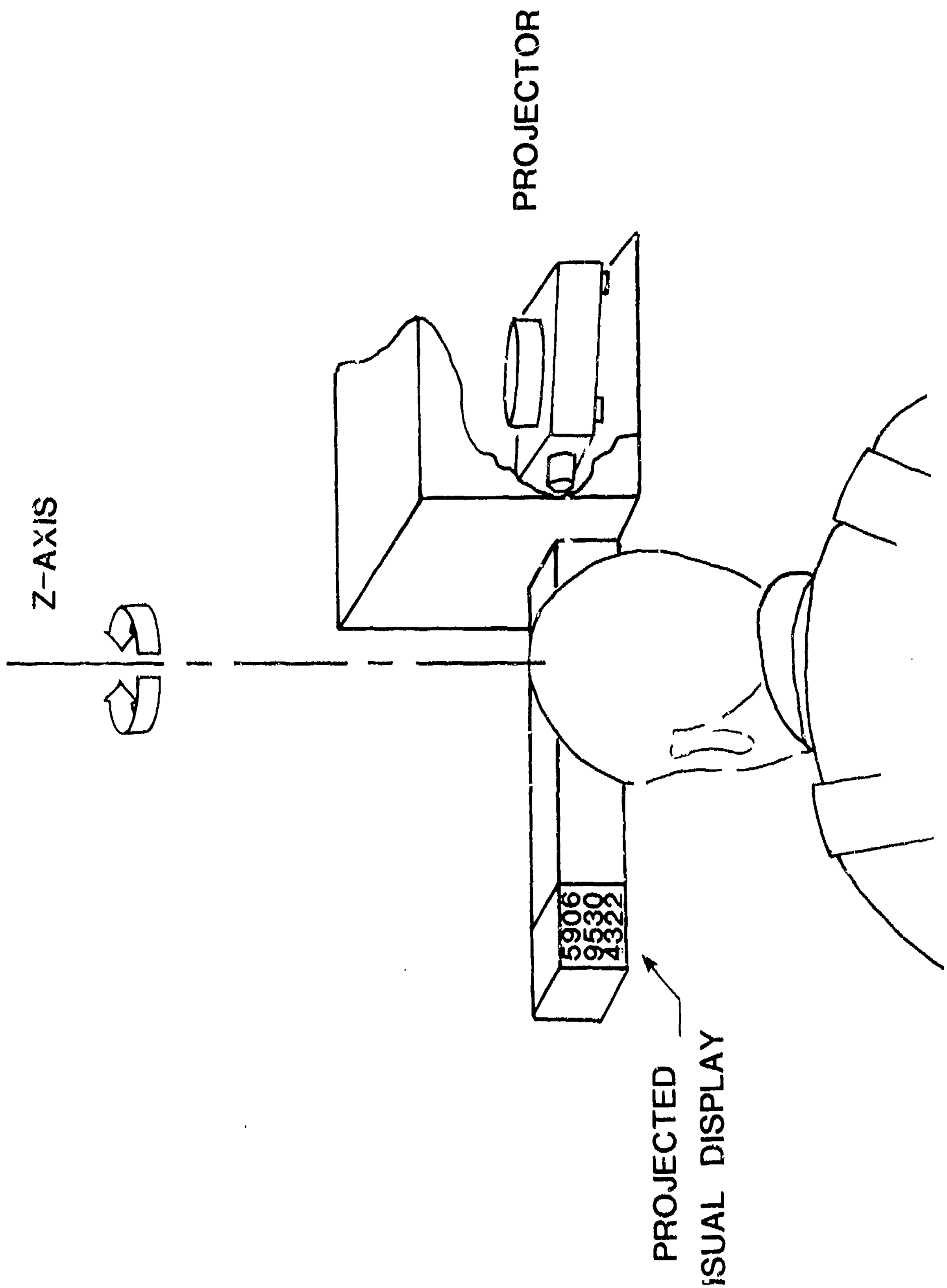

Fig. 1. Diagram illustrating the position of the subject in relation to the projected visual display.

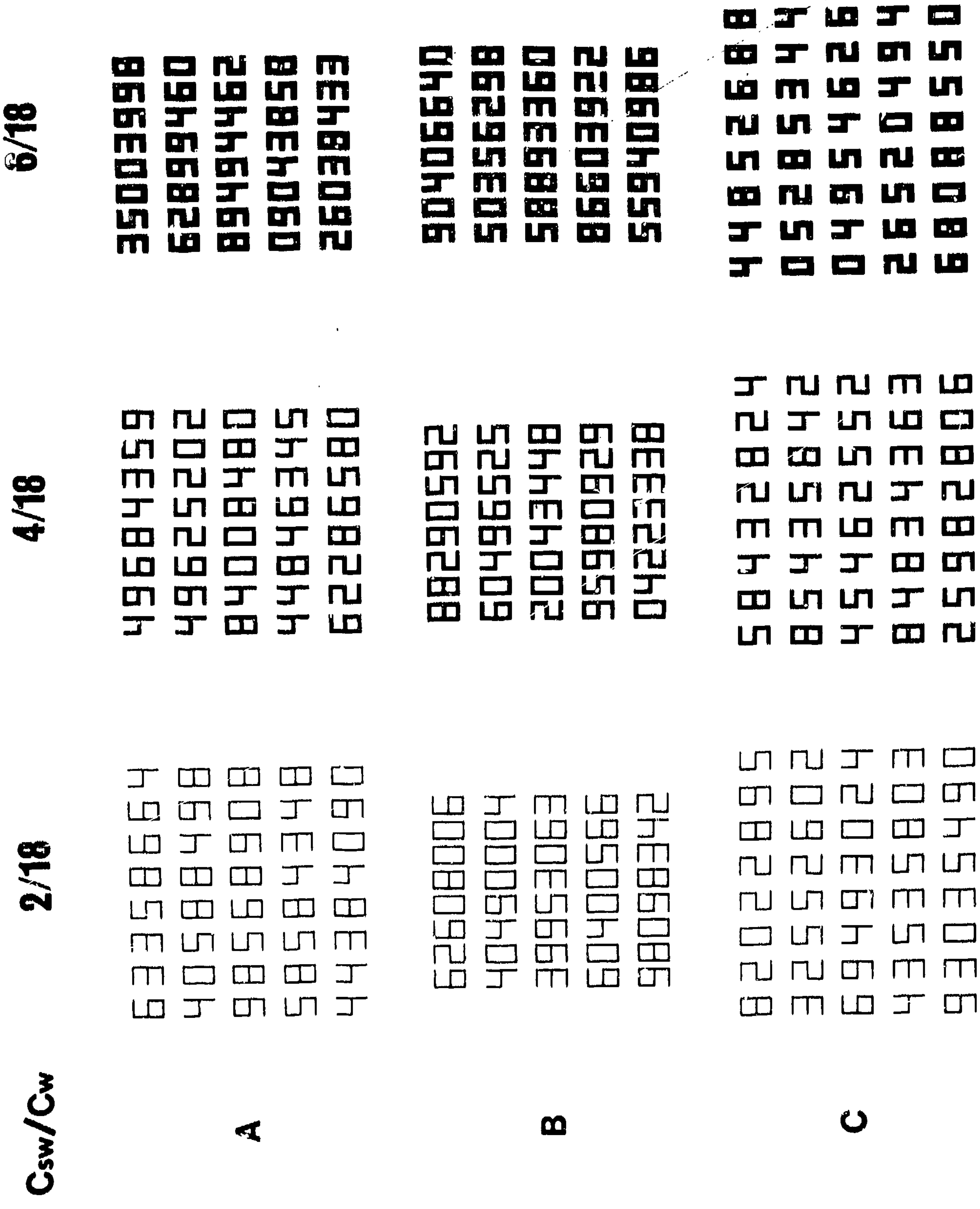

Fig. 2. Examples of the three digit matrix formats (A, B & C) presented to the subject. In each format there were 5 character stroke-widths, three of which are illustrated here.

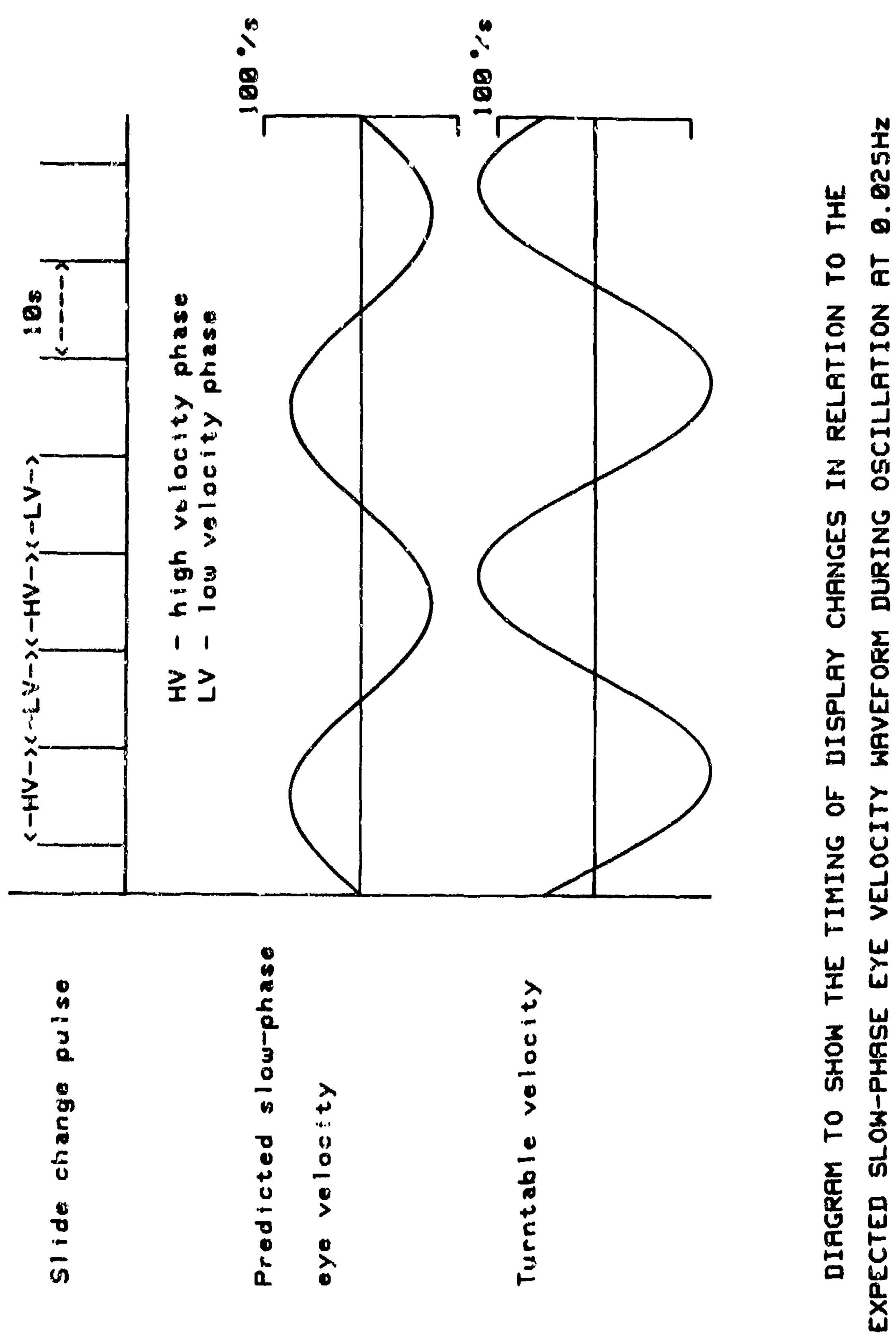

Fig. 3. Relationship between the turntable velocity stimulus, the expected slow-phase velocity component of the vestibulo-ocular reflex response and the timing of the pulses used to initiate slide change and presentation of a new visual display.

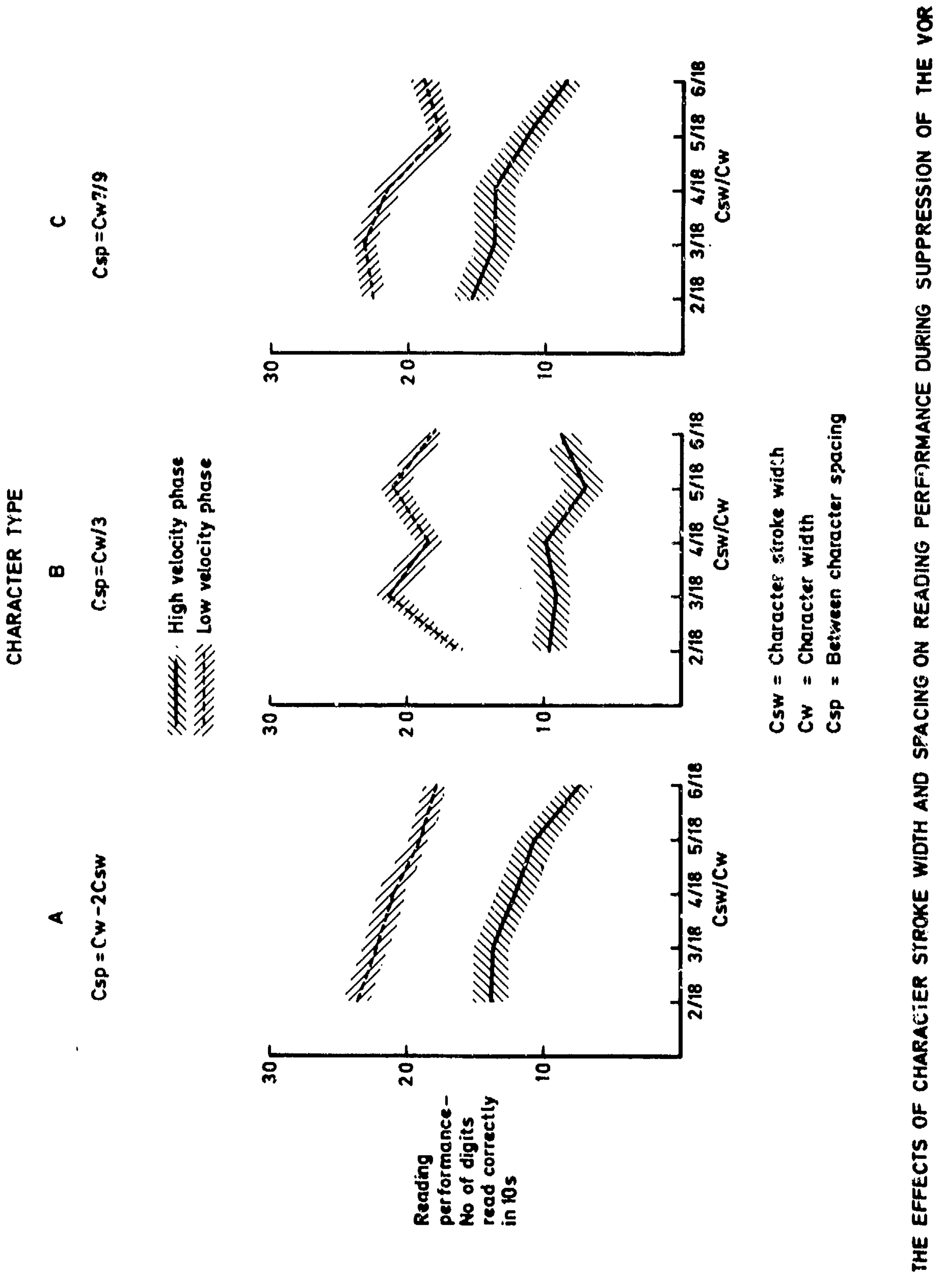

Fig. 4. The effects of character stroke-width on the reading performance for each of the digit matrix formats (A, B & C) shown in Fig. 2. The high and low velocity phases are defined in Fig. 3.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

When man is required to view a head-fixed display during body movement, his reading performance is degraded because of inadequate suppression of the vestibulo-ocular reflex. An experiment has been conducted to ascertain whether visual performance can be enhanced if the characteristics of a visual display are modified. Subjects were exposed to a 0.025 Hz angular oscillation about the yaw axis with a peak velocity of $\pm$ 120°/s. During both the high and low velocity phases of the waveform there was a significant improvement in reading rate when either the stroke-width of the charac-

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